A Survey on Artificial Intelligence in Nuclear Science

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1. Introduction

The recent development of artificial intelligence (AI) has sparked the fourth industrial revolution. As a cutting-edge research field, nuclear science is not an exception, a variety of AI techniques have been successfully applied in the field. Inside the flood of AI researches, understanding the current state of practice is the key for successful implementation of AI. Several previous papers [1-4] reviewed the literature on machine learning and deep learning in nuclear science and associated engineering fields. Even though the authors gave an organized review of various applications, however, the results are based on qualitative analysis. In order to investigate the research trend of AI in nuclear science and find valuable insights in a quantitative manner, we apply text mining techniques to the extensive document datasets. A similar work by Lim and Maglio [5] examined the massive scientific and news articles using a combination of metrics and machine learning algorithms to understand the literature of smart service systems. In this way, we can systematically study the literature and obtain valuable quantitative results.

In this paper, we provide a data-driven survey on AI applications in the nuclear science domain based on the quantitative analysis on the literature. The remainder of this paper is organized as follows. In Section 2, we describe the collection of datasets. The methodologies and results on the research articles and the national R&D project of Korea data are given in Section 3 and 4, respectively. In Section 5, we conclude with a summary of findings and a discussion of future direction.

2. Data Collection

2.1 Collection of the Research Articles

First of all, we collected research articles in nuclear science from the Scopus database [1] with their bibliographic data such as the title, abstract, keywords, information of authors and publication, etc. Since nuclear science has a wide range of research topics, we limit the scope to the *articles* published in the *journal* with respect to the following Journal Citation Reports[2] categories: a) Nuclear Physics, b) Nuclear Science & Technology. The collected 'the base dataset[3]' consists of 65,192 articles from 47 journals published from 2015 to 2020. From the base dataset, we extracted 'the core dataset' of AI-related articles that include at least one of the *query keywords* listed in Table I in their title, abstract or keywords. The query keywords are carefully defined in terms of tasks and algorithms, so as to cover as many AI applications in nuclear science as possible. Table I lists the query keywords where the parenthesis indicates possible variation. Finally, the core dataset contains 1,707 research articles in total. We clean the data using the popular techniques for text data preprocessing such as stop word elimination, lemmatization, and stemming.

Table 1. List of the query keywords for the core dataset

Category	Keywords
Task	artificial intelligent(ce), machine learning, deep learning, data mining, data(-)driven, automated(ion) reinforcement learning, Q(-)learning, (un)supervised learning, clustering, regression, classification, learning algorithm(methodology), digital twin, natural language processing
Algorithm	[Full Names] neural network, fully(-)connected, convolution(al) neural, recurrent neural, generative adversarial network, auto(-)encoder, variational autoencoder, support vector, random forest, gated recurrent unit, decision tree, xgboost, gradient boosting, restricted Boltzmann machine, bayesian network, bayesian neural, k means, k(-)nearest neighbor, bagging [Abbreviations] DNN, CNN, RNN, LSTM, VAE, SVM, SVR, GRU, kNN

2.2 Collection of the Korean National R&D Project Data

In addition to the academic research articles, we are also interested in the data of national R&D projects of Korea for understanding of the research trend in a different point of view. We mainly investigate the number, budget and human resources of the relevant research projects that applied AI techniques in the nuclear science domain. The dataset was obtained from the National Science and Technology Information Service (NTIS) [4], which is an information retrieval system for the national R&D project of Korea. We collected the cases that includes at least one of keyword in each of two query sets: {'원자력 (nuclear power)',

[1] https://www.scopus.com/
[2] https://clarivate.com/webofsciencegroup/solutions/journal-citation-reports/
[3] The date of collection: February 3, 2020
[4] https://www.ntis.go.kr/

'원전 (nuclear plant), '방사능 (radioactivity)'}, {'artificial intelligence', 'machine learning', 'deep learning'}. Table 2 describes the collected dataset by the number of projects and human resources, and the budget expenditures from 2015 to 2019.

Table 2. The number of projects and human resources, the budget expenditures from 2015 to 2019

Year	Project	Human Resource	Budget (1B KRW)
2015	2	2	0.6
2016	8	29	1.35
2017	31	415	11.56
2018	53	557	17.31
2019	71	749	23.36
Total	165	1,752	54.18

3. Trend of Academic Research in Nuclear Science with AI Applications

In this section, we present the analysis of the bibliographic data of 1,707 research articles collected in the core dataset.

3.1 Research trend analysis based on simple statistics

To observe the increase of interests in AI research in nuclear science, we counted the number of relevant publications from 2015 to 2019. As shown in Figure1, the AI research has significantly increased in 2019. Note that 113 articles have already been published at the time of collection (2020. 02. 03.); it is expected to show a dramatic increase at the end of 2020.

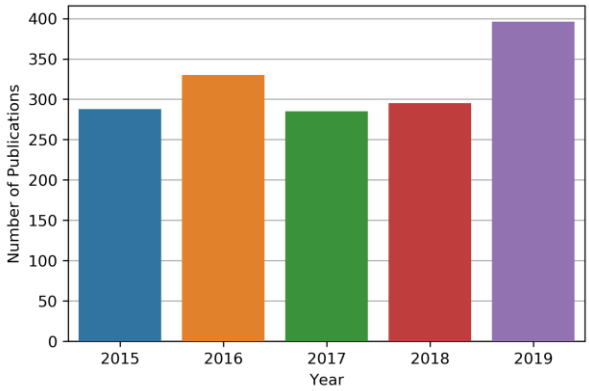

Figure 1. The number of publications of the research articles in nuclear science with AI applications from 2015 to 2019

Figure 2 shows the trend of publications by the keywords (i.e., 'machine learning', 'deep learning', 'reinforcement learning', 'artificial intelligence', 'data mining (or data driven)'). The drastic increase of 'machine learning' and 'deep learning' after 2017 is notable. Despite the increasing attention in AI, applications of advanced AI methodologies tend to lag behind. For example, use of the state-of-the-art algorithms are barely found in the result such as 'generative adversarial networks', 'graph neural networks', 'Bayesian neural network', 'meta learning' and so on. The result implies that the nuclear science domain is still open to the advanced AI techniques.

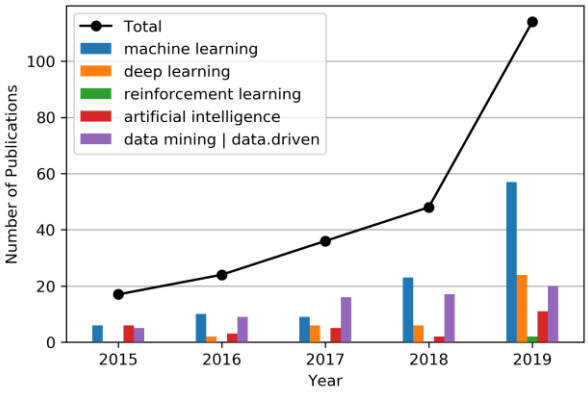

Figure 2. Publication trends of AI in nuclear science

3.2 Network analysis of researchers

In order to investigate the relationship among the researchers (or affiliations), we perform the network analysis based on the co-occurrence matrix. Figure 3 illustrates co-authorship networks where the node size and edge width indicates the number of publications and co-authored publications, respectively. Note that the two-colored huge network in the middle shows the works by global collaboration of ALICE and ATLAS at CERN.

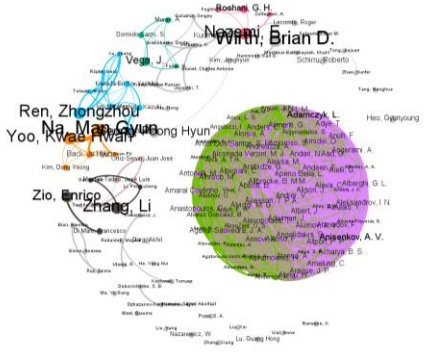

Figure 3. Network analysis of the researchers

3.3 Keyword analysis using word clouds

In order to figure out the relationship among keywords related to AI, we examined the data through descriptive analyses using word clouds. Given a word of interest, we constructed a word cloud with the keywords occurring in the title, abstract and keywords of the article that includes the given word. The word size indicates their count of occurrence. For example, Figure 4 shows the most-frequently occurring words in the articles that include 'artificial intelligence' in their keywords. This

visualization implies that the methodological terms such as ‘machine learning’, ‘neural network’, and ‘fuzzy’ are involved in the articles. For the application area of AI, on the other hand, we can see ‘fault diagnosis’, ‘imaging’, ‘tomography’ and ‘biomedical’ have been selected the most.

Figure 4. Word cloud of the articles that include ‘artificial intelligence’ in the keywords

Figure 5 illustrates the word cloud of ‘LSTM’, which is a deep learning method for sequential data analysis. As shown in Figure 5, we assume that LSTM has been used for ‘anomaly detection’ of ‘time series’ data in ‘reactor’ and ‘pressurizer’.

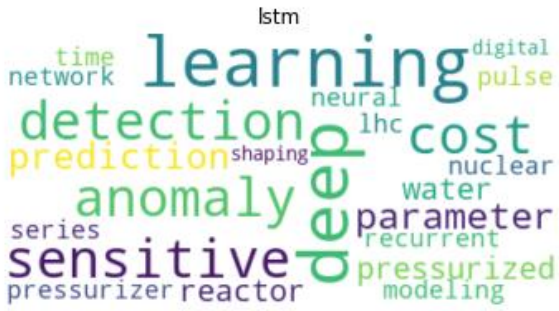

Figure 5. Word cloud of the articles that include ‘LSTM’ in the keywords

4. The National R&D Projects of Korea in Nuclear Science with AI Applications

In this section, we review the national R&D projects of Korea in nuclear science with AI applications. In particular, we are interested in the following questions: (1) *How many* AI-related projects have been carried out in recent years? (2) *Which institutions* have been involved in the projects? (3) *Which AI techniques* have received attention in the projects?

4.1 The overall quantitative trends of the R&D projects

First, we analyze the quantitative trends of the national R&D projects of Korea in nuclear science with AI applications. Figure 6 illustrates the number of projects and participants, and the executed budgets of the projects from 2015 to 2019. It is notable that the statistics dramatically increased in 2017. We assume that the increment is related with the big event in AI, which is the Go match Sedol Lee versus AlphaGo. Actually, we found two projects that directly refer to AlphaGo [6]. Compared to the drastic growth of the participating human resources, the number of projects and their budgets have not increased so much. The amount of executed budget on the relevant projects is only 1.81% of the whole budget in 2019.

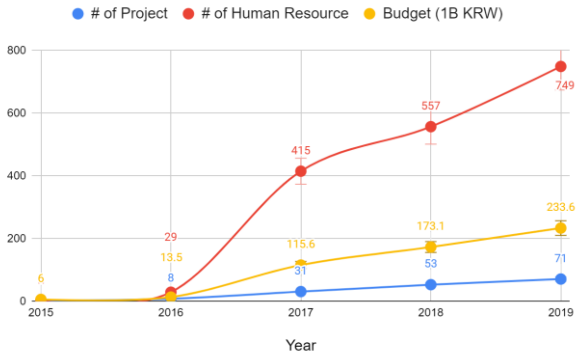

Figure 6. The overall trends of the national R&D projects of Korea in nuclear science with AI applications from 2015 to 2019

4.2 Institutions participating in the R&D projects

Figure 7 shows the ratio of budget executed by different institutions for the AI-related R&D projects from 2015 to 2019. Korea Hydro and Nuclear Power (KHNP), Pukyong National University (PKNU), and Korea Atomic Energy Research Institute (KAERI) are the biggest stakeholders on the portion of 27.6%, 19.1% and 12.3%, respectively. In addition, we found that these three institutions have different interests in subjects as follows:

- KHNP: development of operation-supporting technology using AI for nuclear power plants
- PKNU: aseismic performance improvement of nuclear power plants against earthquake hazards
- KAERI: reliability of material degradation diagnosis

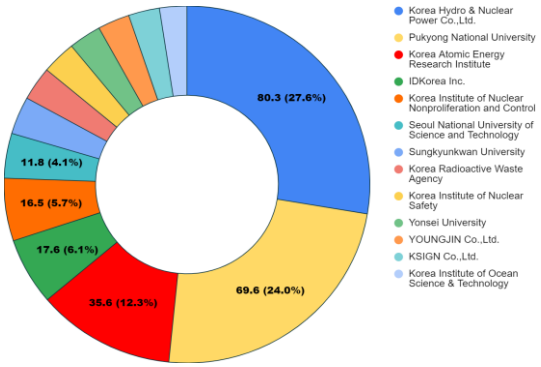

Figure 7. The ratio of budget executed by different institutions for the AI-related R&D projects from 2015 to 2019

4.3 AI techniques applied in the R&D projects

In order to figure out the AI techniques of interest in the R&D projects, we analyze the newly emerging keywords in each year from 2016 to 2019 as listed in Table 3. In 2016, 'Machine Learning' and 'Deep Learning', which are general terms of AI, began to appear in the titles of the projects. It is interesting that 'Deep Learning' has never appeared before 2016 even though it gained a lot of attention in a variety of fields since 2013. Afterwards, the keywords representing specific techniques or approaches such as 'Transfer Learning', 'Reinforcement Learning', 'Variational Autoencoder' and 'Generative Adversarial Network' appeared from 2017 to 2019. The diversity of newly emerged keywords clearly suggests that the nuclear science field has gradually applied AI techniques.

Table 3. Newly emerging keywords from 2016 to 2019

Year	Keywords
2016	Deep Learning, Machine Learning
2017	Transfer Learning
2018	Reinforcement Learning, Variational Autoencoder
2019	Generative Adversarial Network

5. Conclusions

In this paper, we survey the current research trends of AI applications in nuclear science based on the extensive literature review. We applied the text mining techniques on the relevant research articles and the national R&D projects in Korea for the comprehensive and quantitative analysis. As a result, we found a dramatic growth of AI applications in nuclear science in academic research as well as the national R&D projects. We suggest that AI-related research in nuclear science will keep growing along with the rapid advance in AI techniques.

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